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Optimum Tie Constraint at Screws Spacing in Cold-Formed Steel Built-Up Box Beams Subjected to Four-Point Flexural Loading

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ABSTRAK

Cold-formed steel has many advantages, including high strength, lightweight, fast and practical installation, durability, recyclable, non-combustibility, and simple manufacturing procedures. In general, the open section beams are used widely in roof construction. However, since the shear center and the centroid of the cross-section do not coincide, open-section beams are prone to instability modes. To address this issue, researchers have used doubly symmetric built-up sections or built-up closed sections beams. This study presents an experimental investigation on Cold-Formed Steel (CFS) built-up box beams with varying screw spacing arrangements. Six beam specimens, each with a span of 1300 mm, were subjected to four-point bending tests. The beams were fabricated from C75×35 profiles with a thickness of 0.75 mm, assembled face-to-face into built-up box sections using self-drilling screws positioned along the flanges to act as tie constraint at screws. Three screw spacing configurations were considered—H, 2H, and 5.5H—where H denotes the section depth. All tests were conducted under simple support conditions. Experimental testing was performed using a Universal Testing Machine (UTM) with a displacement-controlled loading rate of 0.5 mm/min. Findings indicate that screw spacing significantly influences the flexural behavior of CFS built-up box beams. Based on the outcomes, a screw spacing of 5.5H is recommended for design applications under four-point bending conditions.

***Kata kunci**: tie constraint at screws spacing, cold-formed steel, built-up box beams, experiment*

1. INTRODUCTION

Cold-formed steel (CFS) offers a high strength-to-weight ratio, structural rigidity, design flexibility, recyclability, fire resistance, cost efficiency, [1], [2], [3], [4], and uniform manufacturing quality when compared with hot-rolled steel [1], [5]. Its lightweight nature, precise geometries, and smooth finishes facilitate superior quality control and rapid installation in modern construction. In applications such as framing, purlins, trusses, and floor systems, beam design must address moment capacity, stiffness, shear, bending–shear interaction, web crippling, buckling resistance, and span length, the latter typically governed by deflection for long spans, bending for medium spans, and shear for short spans [6], [7].

Structural instability is a critical concern in the performance of CFS members, as their high slenderness ratios make them susceptible to buckling prior to yielding. CFS members may exhibit several buckling modes, including local, distortional, flexural, and lateral–torsional buckling, depending on their cross-sectional geometry and length [8]. The primary buckling modes include: local buckling, in which individual plate elements such as flanges or webs deform under compression, reducing stiffness without necessarily causing immediate failure [2], [6], [7], [9]; lateral-torsional buckling (LTB), a global mode involving twisting and lateral displacement of the cross-section under bending [10], [11], which can be mitigated by providing lateral restraints [12], [6]; and distortional buckling, characterized by deformation of the cross-sectional shape, often from flange-lip or web bending, which is particularly critical in open thin-walled sections [9], [7]. In addition, flange buckling is often the dominant failure mechanism, occurring as the stress distribution increases uniformly from the center of the cross-section toward the flange tip [8].

CFS members are often manufactured as singly symmetric or point symmetric open sections due to flexibility and ease of production. However, such open sections possess very low torsional stiffness. To overcome this issues, CFS can be fabricate into built-up sections [13]. By connecting two channel members with self-drilling screws, built-up sections can be formed. These built-up sections may be arranged in various configuration, including back-to-back (BTB), face-to-face (FTF), box sections, gapped, angle, or other cross-sectional forms [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23]. The use of tie constraint at the screws located on the top and bottom flanges helps prevent the individual sections from buckling independently [13],[17]. Nevertheless, the built-up sections are only connected at discrete points along the member length, making the structural behavior of CFS built-up section is more complex than that of cold-formed single open sections [6].

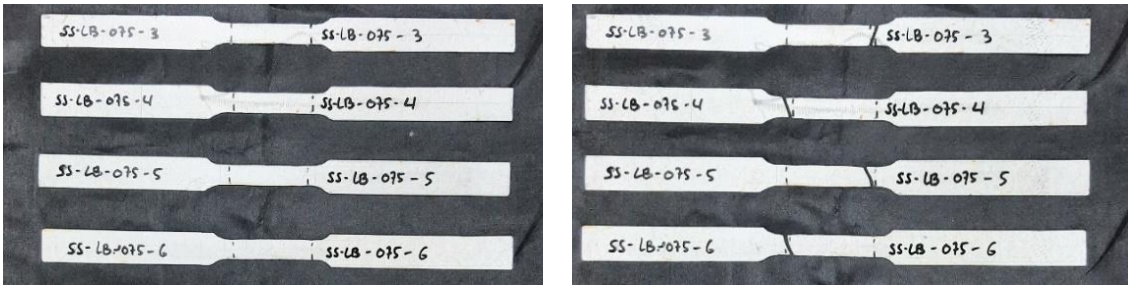
This study aims to investigate the tie constraint at screws spacing of CFS built-up box beams specimens under four-point flexural loading. The placement of non-screwed wooden block at the location of the concentrated load for several beams will also be studied and compared to those beams without non-screwed wooden block. The present study differs from previous works [13], in which wooden blocks were mechanically connected to the CFS using screws or bolts. The mechanical behavior comparison between those two kinds of beams will be presented in terms of load–vertical displacement, moment–curvature relationship, and failure mode.

2. METHODS

2.1 Material Properties

Consistent with the previous studies [24], [25], in the present investigation the profile used is C75×35 x 0.75 mm^3 with material property of G550. Coupon test was carried out to determine the material tensile properties based on ASTM E8/E8M. The flat coupon has a nominal width

of 12.5 mm and a gauge length of 50 mm. The coupons were taken from the center of the web plate, top and bottom flange in the longitudinal directions of the untested specimens. Those locations were chosen since the material had not been subjected to significant stress. It is also destinated to have insight of the specimens yield strength from different locations of the profile. The coupons were tested in a 500 kN Universal Testing Machine (UTM) with displacement control of 0.84 mm/min. The average yield strength of the six specimens is 554.48 MPa. Four of the six specimens before and after tensile test can be seen in **Figure 1**.



(a) (b)

Figure 1. Coupon specimens: (a) before tensile test, and (b) after tensile test

2.2 Test Specimen and Labelling

Self-drilling screw M2 12-14 x 20 (AISI C1022 Low Carbon) was used as tie constraint at screws to join the face-to-face built-up box beams specimens, as shown in **Figure 2**.

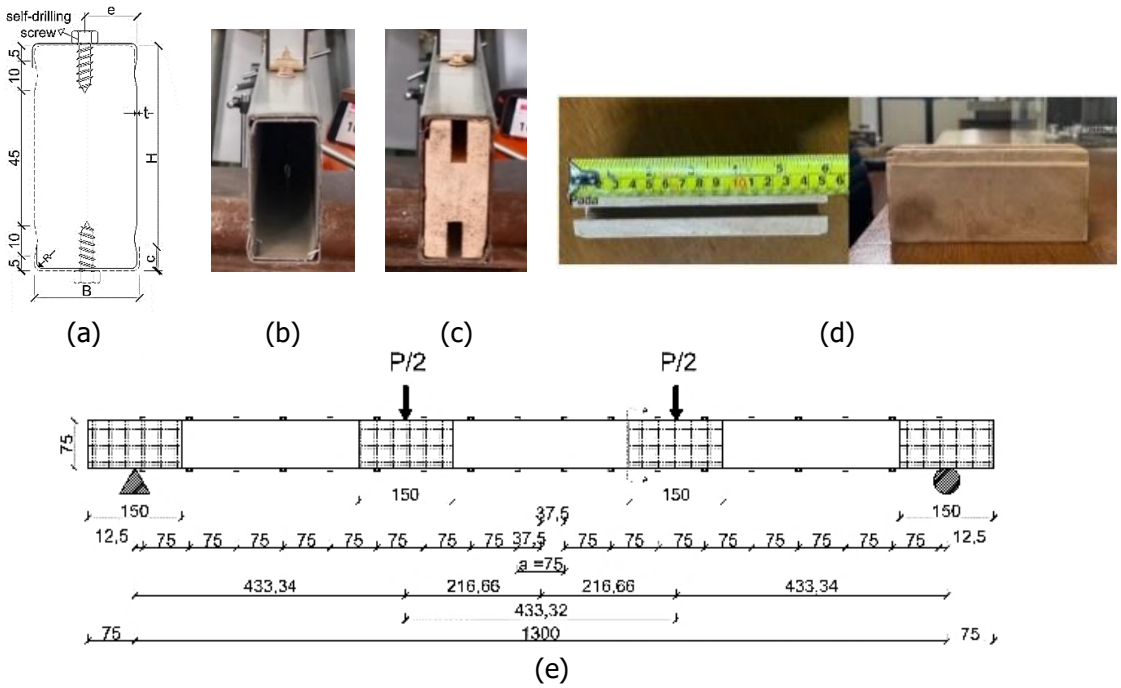


Figure 2. Illustration of the non-screwed wooden block applied in four-point flexural loading: (a) box profile (b) actual profile without wooden block, (c) actual profile with wooden block, (d) geometry of the wooden block, and (e) its placement along the beam

Throughout the longitudinal span of the top and bottom flanges of the beams, the tie constraint at screws spacing was placed differently for beams. The three different spacing are H, 2H, and 5.5H, where H is the specimen height, as illustrated in **Figure 3**.

The labelling of the specimens to identify simplified as "5.5H WF", where "5.5H" indicates the tie constraint at screw spacing; and "W" denotes a non-screwed wooden block serving as stiffeners, "F" represents that the sample is tested under four-point flexural loading, as presented in **Figure 4** and **Table 1**.

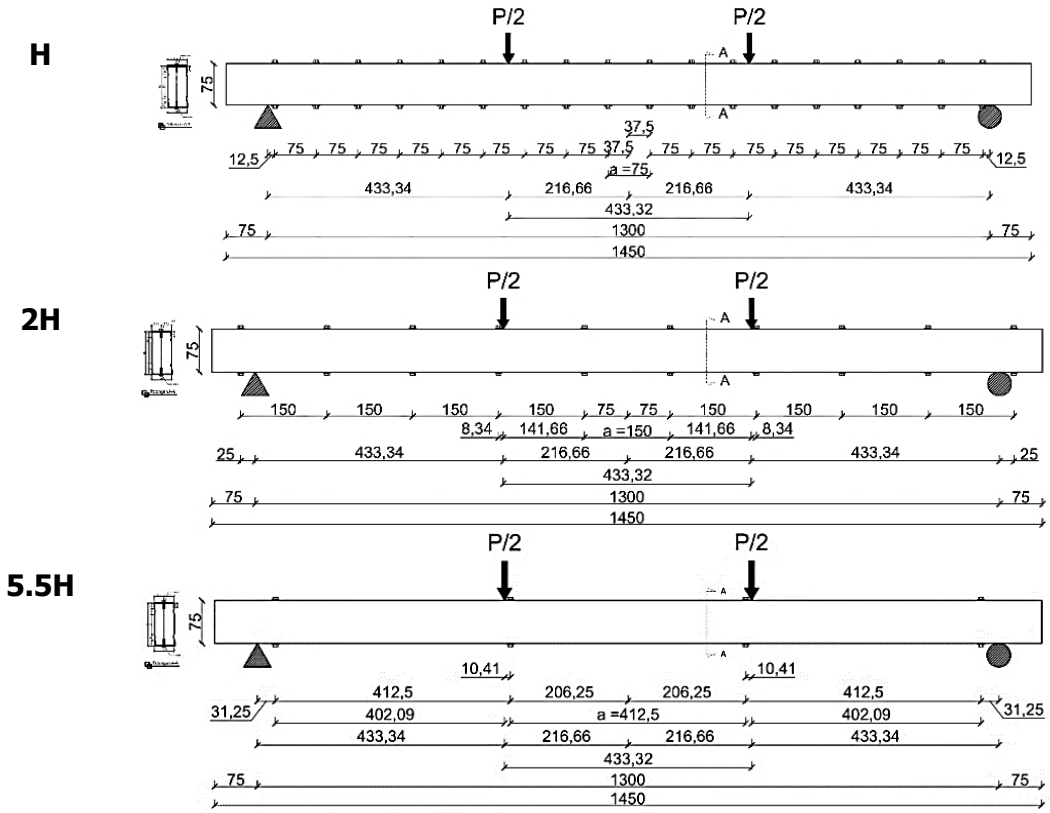


Figure 3. Tie constraint at screws spacing

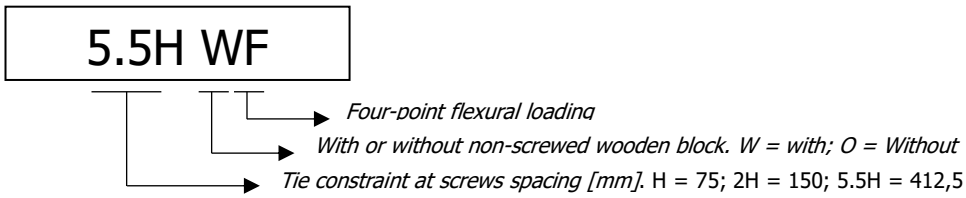


Figure 4. Specimen labelling

Table 1. Specimen Configuration

No.	Specimen	Presence of non-screwed wooden block	Tie constraint at screws spacing [mm]
1	H OF		75
2	2H OF	Without non-screwed wooden block	150
3	5.5H OF		412.5
4	H WF		75
5	2H WF	With non-screwed wooden block	150
6	5.5H WF		412.5

2.3 Experimental Set-Up

Six built-up box beams where each of them has a length of 1,500 mm; were tested using four-point flexural loading scheme. Pinned and roller supports located at their ends defining a span of L = 1,300 mm; as shown in **Figure 5**. A Universal Testing Machine (UTM) with a maximum capacity of 50 kN was employed to test all specimens under a displacement control rate of 0.5

mm/min. The actuator was connected to a spreader beam, which has a length of L/3 or 433.33 mm to enable the test scheme. To measure the vertical deflection of the beam, three Linear Variable Differential Transformer (LVDT) were placed at the bottom flange of the beam on 0.25L, 0.5L, and 0.75L perpendicular to the beam. LVDT reading data are recorded every 60 seconds for each beam specimen. Slope at the support of the beam is measured manually by means of two inclinometers which are placed near the two supports. During the test, the displacement and load were recorded using a data acquisition system.

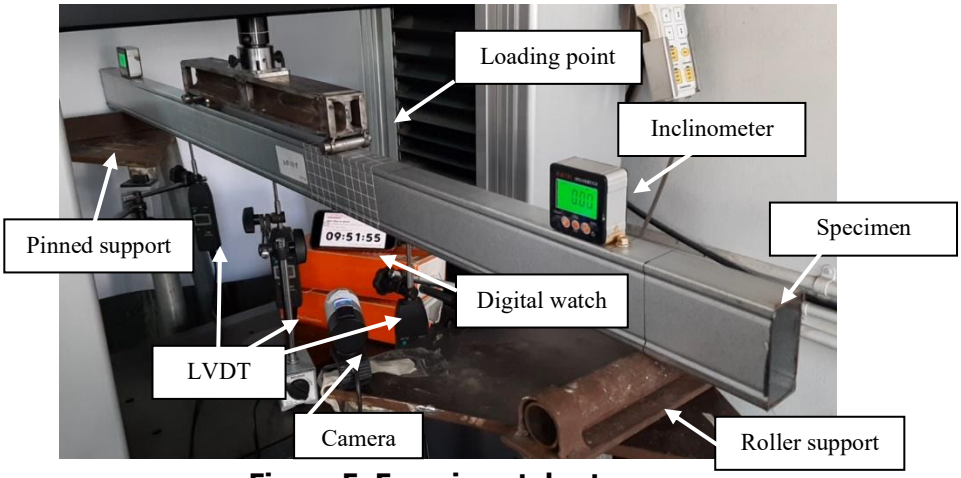
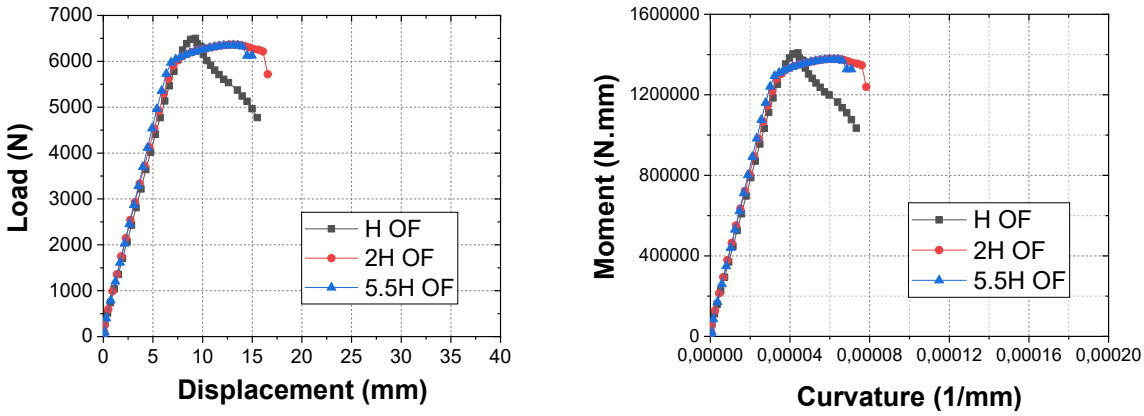


Figure 5. Experimental set-up

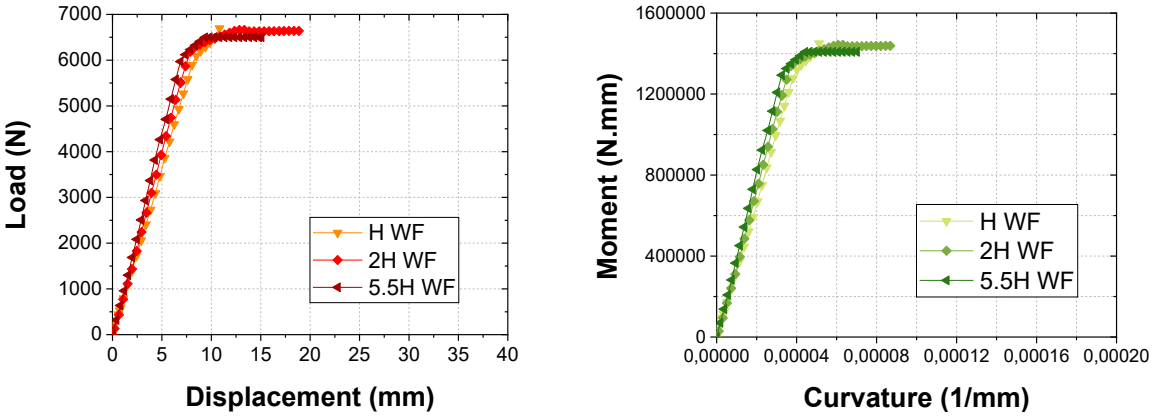
3. RESULTS AND DISCUSSION

In determining optimum tie constraint at screws spacing, six specimens-H OF, 2H OF, 5.5H OF, H WF, 2H WF, and 5.5H WF-were tested. The load-vertical displacement and moment-curvature responses of these specimens are illustrated in **Figure 6, Figure 7,** and **Table 2**.



(a) (b)

Figure 6. (a) Load-Vertical Displacement, and (b) Moment-Curvature relationship from specimens without non-screwed wooden block



(a) (b)

Figure 7. (a) Load-Vertical Displacement, and (b) Moment-Curvature relationship from specimens with non-screwed wooden block

Figures 6 and **Figure 7** present the load–vertical displacement and moment–curvature relationship of the six specimens, respectively. All beam specimens reached peak loads between 6,000 to 6,700 N; while their peak moments ranged from 1,300,000 to 1,500,000 N·mm**;** reflecting their flexural strength. However, the H OF configurations exhibits a sharp post-peak drop in both load and moment. All WF specimens, except H OF specimen, still redistribute moment after yielding. The descending curve could not be captured as the LVDT has a measurement limit of 25 mm while the LVDT used could not beneficiate this maximum capacity for safety reasons. The beam specimens with non-screwed wooden block shows the highest ultimate load compared to those beams without non-screwed wooden block, where WF specimen variants showing, on average, almost 4% higher ultimate load than those OF specimen variants, as shown in **Table 2**. All beam specimens exhibit similar initial stiffness up to approximately 7 mm vertical displacement-still in the elastic range-indicating consistent elastic behavior of all specimens before developing their non-linear behavior. Nevertheless, 5.5H WF beam presents slightly higher flexural stiffness compared to the OF variants, H WF and 2H WF. The WF variants also demonstrated that the non-screwed wooden block functions sufficiently as a stiffener, even without screws at the interfaces between the webs and the side surfaces of the wooden block, as well as between the flanges and the top and bottom surfaces of the wooden block.

Table 2. Experimental Result Comparison Under Ultimate Load

Specimen	P_{EXP} [N]	P_{EXP} percentage difference between WF and OF [%]
H OF	6,499.003	3.000
H WF	6,693.985	
2H OF	6,361.400	4.718
2H WF	6,661.526	
5.5H OF	6,349.956	2.397
5.5H WF	6,502.176	
Average		3.327

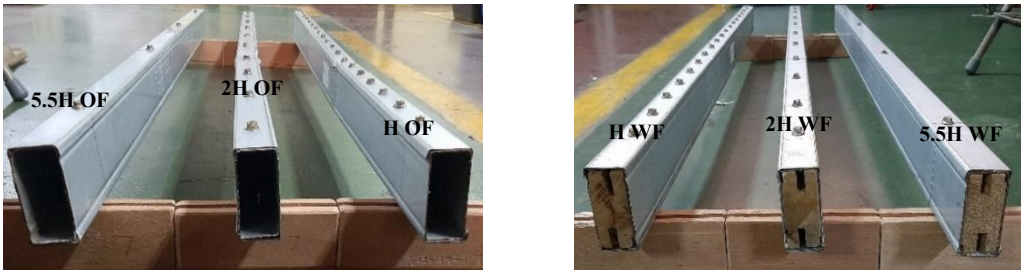
In addition to stiffness, the optimum tie constraint at screws spacing is determined by two other conditions. The first is the minimum linear vertical displacement at the beam's mid-span under a maximum elastic load of 6000 N, as shown in **Table 2**, where the 5.5H WF beam exhibits the smallest vertical displacement of 7.04 mm. The second condition is the minimum total number of tie constraints, as indicated in **Table 3**.

Table 3. Vertical Displacement of H, 2H, and 5.5H Built-Up Box Beam Specimens Correspond to Maximum Load (P) 6000 N

Specimen	Vertical displacement	
	δ_{EXP} [mm]	δ_{EXP} deviation to 5.5H [%]
H WF	8.05	14.34
2H WF	7.59	7.79
5.5H WF	7.04	0.00

Table 4. Tie Constraint at Screws Number Comparison Between H, 2H, and 5.5H Built-Up Box Beam Specimens

Specimen	Number of tie constraint at screws	Percentage of tie constraints at the screws number relative to 5.5H [%]
H WF	36	350
2H WF	20	150
5.5H WF	8	100



(a) (b)

Figure 8. Deformation comparison between specimens after the test. (a) without non-screwed wooden block and (b) with non-screwed wooden block

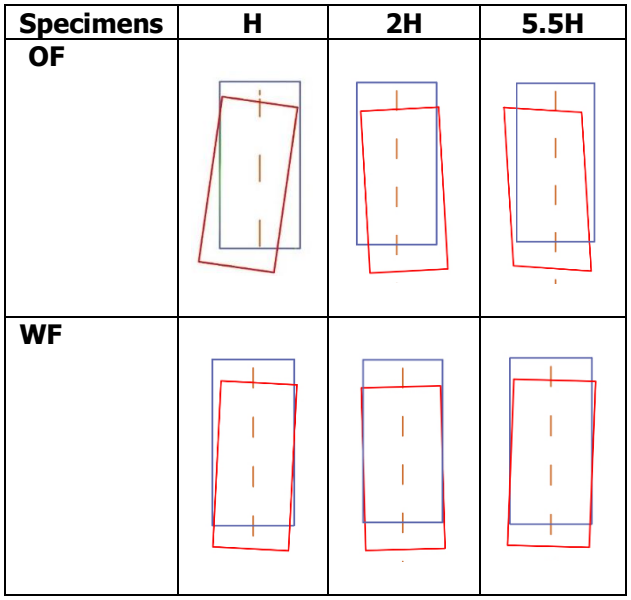


Figure 9. Mid-span lateral displacement and rotation of the six specimen profiles at maximum load measured with laser distance digital apparatus. Blue line (before loading application), and red line (at maximum load)

Table 3 and 4 show that the number of tie constraint at screws in the H and 2H beam specimens is considerably higher than that in the 5.5H beam specimen, while the 5.5H specimen used only 8 tie constraints, achieved the lowest vertical displacement among all variants WF. Despite fewer ties, 5.5H also offers better ties efficiency than those of H and 2H section condition after the test. **Figure 8** presents global condition of the six beam specimens

after the test. **Figure 9** shows the condition of the profile sections located at the beam mid span for the six beams at maximum load. This Figure also presents vertical displacements and rotation of the profile section at beam mid span from all OF and WF variants which are obtained with the aid of laser distance apparatus during test. Blue line shows the profile section before the load application, and the red line indicates the profile section condition at the maximum load. Here we can see that the 5.5 H WF mid span section experiences smaller vertical displacement and lateral rotation compared to the other sections. **Figure 9** confirms that 5.5H WF beam provides better stability compared to those OF variants, H WF and 2H WF beam.

4. CONCLUSION

The study explores the optimum tie constraint at screws spacing of CFS built-up box beams under four-point flexural loading. The key observation from the experimental findings indicates that this spacing play a crucial role in the ultimate load capacity, deflection, and lateral rotation performance of the tested specimens.

The inclusion of a non-screwed wooden block increases slightly the specimen's ultimate load capacity compared to a beam without this feature. This indicates that the presence of a wooden block, even without direct attachment, contributes to better load distribution and possible delays localized failures and improving overall strength. Furthermore, deflection results show that the 5.5H WF configuration with the non-screwed wooden block exhibits the lowest deflection among the tested specimens with non-screwed wooden block, implying improved rigidity.

On the other hand, the H and 2H WF configuration demonstrate that bigger number of tie constraints at the screws compared to 5.5H configuration may lead to an increase in installation time and cost but did not give better mechanical responses. Finally, this study concludes that the 5.5H WF CFS built-up box beam specimen under to four point bending test, performs better than the other beams in terms of flexural strength, deformation, installation time and cost. Hence it is recommended that further experimental research is needed to find the optimum tie constraint at screw spacing at cold-formed steel built-up box beams facing to unsymmetrical loading condition.

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